NATIONAL BUREAU OF STANDARDS REPORT

8960

Development of Improved Method for
Measurement of Spectral Irradiance
from Solar Simulators

Progress and Status as of July 31, 1965

by

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Metrology Division
National Bureau of Standards
Washington, D. C.

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I. INTRODUCTION

In previous reports (1, 2) a considerable amount of basic information was included covering the standards, the detectors, and the preliminary status of the general instrumentation under development at this Bureau for use in the measurement of the spectral irradiances from solar simulators. This report will give primary consideration to new developments and to details of instrumental design. While there will necessarily be some duplication, repeated reference to the earlier reports may be required for complete information.

II. Detectors

For use in the precise measurement of spectral radiant energy (in particular spectral irradiance) several types of detectors are available. In cases where sufficient flux is available a thermoelectric detector (thermopile or thermocouple) is to be preferred because of its relatively neutral character as a function of wavelength. Next in line of preference is the use of a photoelectric cell (photoemissive or photoconducting) since the associated electronics may be of rather simple design. However, in certain cases these lack the required sensitivity - thus necessitating the use of photomultipliers with more complicated associated electronics. The latter have been found necessary for the ultraviolet spectral region when employing some of the preferred instrumentation.

1. Thermopiles and Thermocouples

Some of the characteristics of thermal detectors (thermopiles) have been discussed in considerable detail elsewhere (1,2,3). While most thermal detectors lack complete equality of response with wavelength it has been found that coatings of some of the common blacks, for example, gold black or lamp black, if of sufficient thickness, are relatively neutral in spectral response from the ultraviolet to above 4 microns (see figure 1). Parson's black has been found to be neutral in character to above 20 microns (4). Its use may not be satisfactory, however, since a detector coated with it is very sluggish in response, requiring minutes for a full deflection. The use of thermopiles in connection with the present report has been confined to instrumentation employed in measurements involving the setting up of the standards of total and spectral irradiance. Their use in instrumentation for measuring the spectral irradiances of solar simulators has been investigated extensively by others (5). Our work has accordingly been confined primarily to photoelectric instrumentation.

2. Phototubes

A number of phototubes having high sensitivity in the ultraviolet and visible portions of the spectrum are available (6). Among these is RCA-type 935, which is enclosed in an envelope of high ultraviolet transmittance. A typical spectral response for one of these phototubes is shown in figure 2. Its useful spectral range is from 0.25 to about 0.60 micron and it is readily adaptable for use with dc amplification or with conventional or tuned ac amplification following signal chopping.

3. PbS Cells

Among the photoconducting cells the PbS cells appear to offer the best all-around characteristics for use as detectors within the spectral range of about 0.5 to 2.5 microns. These have certain defects as previously noted (1,2) and require hermetic sealing to eliminate short-term variations in sensitivity because of temperature and humidity changes. Higher sensitivity is obtainable through refrigeration and special care as to selection of cell size, orientation, and circuit arrangement (6,7,8,9) but operation at room temperature is usually satisfactory if the auxiliary electronics are adequate. A representative spectral response curve of a typical PbS cell operated at room temperature is illustrated in figure 3.

4. Photomultipliers

Photomultipliers are available with variable characteristics in many sizes and shapes from numerous sources (6). The possible use of several types was discussed in our previous reports (1,2). Recent measurements with an EMI type 9558 QA multiplier have been highly satisfactory. This tube has an S-20 surface and is usable with high signal to noise gain from 0.25 to about 0.80 micron. A representative spectral response curve for this multiplier is given in figure 4.

III. Standard Sources

As indicated in previous reports (1,2) three standards of radiation enter into the development and use of instrumentations for the measurement of the spectral irradiances from solar simulators. These are the standards of total irradiance, of spectral radiance, and of spectral irradiance. All are based upon the radiance of a blackbody as defined by the Stefan - Boltzmann and Planck laws of radiation.

1. Standard of Total Irradiance

Since 1913 the carbon-filament lamp (10) has been employed as a working standard of total irradiance. As set up the irradiance from the entire lamp bulb and socket was included. As a result about 10 percent of the irradiance consists of flux of wavelengths longer than about 3 microns - flux lying within that spectral region highly susceptible to absorptance by atmospheric water vapor. Needs for higher accuracy and wider ranges of total irradiance have necessitated work toward the setting up of three sizes (100-, 500- and 1000-watt) of tungsten-filament lamp standards of

total irradiance. These lamps operate at a higher temperature than is possible with the carbon-filament lamps, and are shielded, except for a narrow area of the bulb in front of the filament, so that the reception of long-wavelength flux from the lamp is reduced to a minimum. The new lamps are being compared with a blackbody at a known temperature, the flux from which is limited in spectral range through the use of a calibrated quartz glass plate. Since no significant flux having a wavelength longer than about 4.5 microns is present from either the blackbody or lamp, errors resulting from water vapor absorption are reduced to a minimum. Higher accuracies in calibrations should result from the use of these standards.

2. Standard of Spectral Radiance

These standards are not used directly in the calibration of instrumentation employed in the measurement of the spectral irradiances from solar simulators or simulator sources. In this area their principal use has been that of an intermediate step in setting up the standards of spectral irradiance as discussed in the previous reports (1,2). To date there have been no inter-laboratory checks between these standards and those of other national or other laboratories. However, in the near future it is expected that such a check will be available through the Heat Division of the NBS. For further information relating to this standard the reader is referred to other sources (1,2,11).

3. Standard of Spectral Irradiance

The experimental work involved in setting up the standard of spectral irradiance has been discussed in some detail elsewhere (12). The original lamp standard consisted of a 200-watt quartz-iodine lamp calibrated for spectral irradiance at a distance of 43 cm. Two problems have arisen. First, for much work, the spectral intensities available fall far short of those desired, especially in the ultraviolet. This was the case in particular with measurements of solar radiation, solar simulators, and solar simulator sources. Secondly, the comparison of unlike sources spectroradiometrically has been found to be very difficult when using conventional spectroradiometric equipment (13) because of variations in sensitivity over the surfaces of available detectors and because of non-uniform transmittances over the apertures of commercial spectrometers. By increasing the spectral irradiance from the standard, both of these problems can be solved, or at least reduced in magnitude. In the first problem the ratio of the spectral irradiances from the test and standard sources is reduced while in the second problem a more powerful standard source permits the use of diffusing optics at the entrance slit of the spectrometer. Accordingly transfer has been made to the use of 1000-watt quartz-iodine lamps as standards of spectral irradiance.

The 1000-watt tungsten-filament quartz-iodine lamp chosen for use as the new standard of spectral irradiance is the G.E. type DXW 120-volt, 1000-watt, V-line lamp (see figure 5). This lamp is in commercial production as a photo-flood source and should continue to be readily available. This was an important consideration in the decision to specify this particular lamp because of previous experiences with non-commercial sources.

The 1000-watt lamp is similar in construction to the G.E. model 6A/T4Q/1CL 200-watt lamp previously employed, except that it is slightly larger (approximately 3/8 inch x 3 inches). When the lamp is used as a standard of spectral irradiance the input current is set at 8.30 amperes, resulting in a "color temperature" of approximately 3100°K. At this temperature its useful life (with output change of less than 1 percent) is about 50 to 100 hours - about the same as for the 200-watt lamp (12).

The spectral data for three of the new 1000-watt tungsten-filament quartz-iodine lamps are given in Table I. These data are for a distance of 50 cm when the lamps are operated at 8.30 amperes. It was ascertained that the inverse-square law applied between 50 and 100 cm. Small corrections may be required when the lamps are operated at lesser distances. These standards have been set up with the lamps mounted vertically and operated on ac. However, from data on several lamps it was ascertained that the lamps may be positioned horizontally (or otherwise) or operated on dc without significant change in the output in the specified direction.

a. Use of the Standard of Spectral Irradiance

Each 1000-watt quartz-iodine lamp standard of spectral irradiance is marked with an identifying number at one end of the lamp. The lamp is mounted in a metal support and is calibrated with the numbered end down and with the number on the side away from the detector. Measurements of distance (from the lamp filament) are made along a horizontal axis passing through the center of the lamp filament. The correct vertical position is determined by setting the centers of the upper and lower press seals along a plumb line as viewed from one side of the lamp. The plane of the front surface of the upper press seal is set to contain the horizontal perpendicular to the line connecting the lamp filament center and detector. Precise setting of the lamp as regards to both vertical tilt and rotation about the filament axis is important, since an error of one or two degrees in orientation may result in an error in irradiance of several percent.

The current is set at 8.30 amperes ac, and the lamp is allowed to operate for at least 5 minutes before data are recorded. Any convenient method may be employed to control the current; however, the circuit illustrated in figure 6 has been found very useful in this laboratory. It consists of two variable autotransformers (20-A and 5-A ratings) and a heavy-duty radio-filament transformer. (One-half of a center-tapped 5- or 6.3-V secondary has been found satisfactory for smooth current control).

IV. NBS Instrumentations Employed in Lamp Calibrations and in the Measurement of Solar Simulator Sources

Since the spectral irradiance from the 1000-watt quartz-iodine lamp (see Table I) at 300 nm is approximately 10 times that at 250 nm, at 390 nm approximately 100 times that at 250 nm, and at 700 nm approximately 1000 times that at 250 nm, the instrumentation chosen for spectral irradiances of various sources relative to that from the standard lamp must have very low scattering for flux of the longer wavelengths into the short-wavelength region of the spectrum. A similar precaution applies to the scattering of flux from spectral regions where detector sensitivity is high to spectral regions where detector sensitivity is low.

1. Spectroradiometric Instrumentation

The usual single-prism or grating spectrometer is at once ruled out for use in spectral irradiance work because the scattered flux in the ultraviolet, especially for wavelengths shorter than 300 nm, is excessive. Only a double-dispersion system is adequate for use with continuous sources such as tungsten-filament lamps, the sun, and solar simulators. For a number of reasons, such as multiple orders of spectra, ghosts, and high losses by scattering, the grating type of instrumentation is inferior to that of the conventional double-prism spectroradiometer. The spectroradiometers in use at this Bureau in lamp calibrations and in the measurement of the spectral irradiances from the sun and from solar simulator sources, are built around the Carl Leiss double-quartz-prism monochromator. It was selected because of its compactness, portability, economy, and adaptability for use over an extended spectral range (0.25 to 2.5 microns). The optical layout of this instrument, together with the various auxiliary components forming the complete spectroradiometer, are shown in figure 7.

The double monochromator contains aluminized mirror optics making it possible to operate over an extended wavelength interval (limited only by the prism material) without change in focus or mechanical slit width. The resolving power is high and the energy output has a high spectral purity and a high degree of freedom from scattered radiation. Its compactness and light weight make it adaptable for mounting on an optical bench (a light duty lathe bed). This requirement is important to permit rapid change in observations between the two lamps (or other sources) undergoing comparison.

Two detectors are employed in this spectroradiometer - a photomultiplier to cover the ultraviolet and visible spectral ranges and a PbS cell for the visible and infrared regions. The two detectors are mounted within an aluminum housing on a single, adjustable table so that either can be brought into proper horizontal position behind the exit slit by means of a simple screw adjustment. (At the present time, however, in lamp calibrations, this instrumentation is employed only for the spectral range covered by the photomultipliers - 0.25 to 0.75 micron; a photoelectric filter instrument, described below, is employed for the longer wavelengths. Vertical adjustment for maximum response is obtained by lowering or raising the detector housing.

A prime component of the instrumentation is the diffusing sphere at the entrance slit. This is required as indicated above since all detectors vary greatly in sensitivity over their surfaces and all double-prism monochromators are non-uniform in transmittance over their optical apertures (13). The combination of the two produces very erratic results in irradiance measurements if attempted without a diffuser at the entrance slit of the spectrometer.

The diffusing sphere is not presently available commercially as a finished product, but the necessary components, spun aluminum hemispheres,1/ may be purchased or readily fabricated. The finished sphere may be coated with MgO, either smoked or pressed into place or else sprayed with $BaSO_4$.2/ When required, a sphere roughened and coated with gold provides a higher efficiency in the infrared for wavelengths longer than about 1.6 microns (2).

The use of attenuating screens for obtaining equivalent flux from the two sources under comparison was discussed in considerable detail in our previous report (2) and will not be further discussed here except to point out that their use affords a check on the linearity of the electronics employed if they are selected with holes not significantly smaller than 0.5 mm diameter and if set precisely perpendicular to the flux beam. Screens with very small openings have been found to have non-uniform spectral transmittance indicating flux loss because of interference effects. Each screen must, before use, be checked for spectral transmittance and for variations in transmittance over their areas if accurate results are to be obtained with them.

The output of the photomultiplier may be measured directly with a dc picoammeter in laboratory work wherein manual operation is practicable. This applies in particular in the calibration of 1000-watt quartz-iodine lamp standards of spectral irradiance. In this case after an adjustment of the zero is made, readings are visually observed and recorded alternately for the standard and for the source under calibration for a particular wavelength setting. Any zero drift is corrected from time to time. This method is employed in the calibration of lamp standards of spectral irradiance at this Bureau for the ultraviolet and visible spectral regions where the photomultiplier has a high sensitivity.

1/ Spun aluminum (thickness .04 inch) hemispheres with a 1/2-inch flange may be obtained from The Webber Brass Company, 3344 Payne Avenue, Cleveland 14, Ohio

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2/ High quality MgO and $BaSO_4$ are obtainable from the Ace Scientific Supply Company, 1420 East Linden Avenue, P. O. Box 127, Linden, N. J.

In investigations in which a source differing significantly in spectral quality from that of the standard lamp, as for example, the sun, or a solar simulator source, is to be measured the use of chopped signals and ac amplification has been found highly advantageous as indicated in our previous report (2). Chopping may be at any convenient frequency, but since available commercial amplifiers have set chopping frequencies the choice of amplifier necessarily determines both. To date, best results in signal to noise ratio have been obtained with the Brower Model 129, 33 cps lock-in amplifier.[3/] This amplifier has a gain switch providing variable gains in steps of 2-2-2.5, etc., for a total range of 5,000,000. This is a considerable improvement over the usual instrumentation with gain ranges in steps of 3, 3 1/3, or 10. No attempt will be made to discuss the electronics of the instrument itself as such information is available from the published literature (14,15) and the manufacturer (16).

As noted in our previous report, strip chart recorders are available in finished design from a number of sources. Only coupling networks need be considered in this connection. If a 10-millivolt strip chart recorder is employed - a type G, L&N instrument for example - the coupling network consists of a 22-ohm resistor (only) across the recorder input.

If meaningful source spectra are to be recorded two auxiliary items not readily available commercially are required. These are a wavelength drive and a wavelength indexing mechanism, or its equivalent. Both may be readily constructed primarily from commercial gearing and electrical components and coordinated so that a small pulse, say, of 5 percent full scale, may be superimposed on the recorder tracing at selected wavelength intervals. The wavelength drive and indexing mechanisms employed at this Bureau are shown in figures 8 and 9.

The various gear components are commercial Boston 32-pitch (type G) brass spur gears. When mounted on steel drill rod stock and set into a brass plate frame, smooth operation is assured with but little lubrication required. However, for deluxe operation, ball bearing or special bronze sleeves may be employed. End motion on the gear shafts may be controlled by end plates, sleeves, reduced shaft diameter, or by drilling the shaft bearings only 3/4 of the distance through the plates. The wavelength indexing mechanism consists of three pins on the gear connected with the spectrometer drive shaft which closes a small micro-switch at three arbitrary positions for each spectrometer drum rotation. Each time a contact is made a pulse originating in the electronics (see figure 9) is impressed upon the signal from the amplifier to the recorder resulting in a momentary 5% full scale increase in the value on the strip chart. An auxiliary, manually operated switch permits the temporary elimination of this pulse as desired.

3/ This amplifier is obtainable from Brower Laboratories, Inc., Turnpike Road (Rt. 9), Westboro, Massachusetts 01581

The Brower amplifier set up as described above is equally applicable for use either with a photomultiplier or with a PbS cell. Hence, this instrumentation may be employed through the entire spectral range from 0.25 to 2.5 microns with but a single change in optical and electronic set-up - the changing of detectors at some point in the visible spectrum. Usually, it is more practicable to overlap a significant portion of the visible range to assure the operator that equivalent results are obtained with the two detectors. Ample sensitivity is available for the ultraviolet, visible, and most of the infrared spectral region employing a single sphere coating, either MgO or $BaSO_4$. Any gain through changing to a gold-coated sphere is probably not worth the added effort (2). However, through the use of a block or plate diffuser (2) a significant gain may be had. An auxiliary plate diffuser is accordingly being set up for use in certain solar simulator measurements. Its use will not permit the obtaining directly of precise absolute values of spectral irradiance because of the difficulties of determining precisely the source and standard distances, but good relative spectral values should thereby be obtainable, and it will be possible to use narrower spectrometer slits, thus increasing measurably the instrumental spectral dispersion. From the establishment of one or more points on the resulting curve, the entire spectral irradiance curve of the source may be placed upon an absolute basis.

a. Spectral Irradiance from an Hg-Xenon Source

An example of the results obtainable with our instrumentation is shown in figures 10A and 10B, the spectral irradiance from a 2500-watt Hg-Xenon arc lamp set at a distance of one meter. The irradiance from this lamp consists of two parts - the continuum and the line spectra. The former is obtained through evaluating the lamp irradiance at numerous wavelengths between lines, then extending the curve arbitrarily through the line positions. The resulting curve should be a true representation of the continuum. However, for the lines, a true representation is impractical, since line widths not only vary considerably, but are usually very narrow indeed, so that a true representation would not only be next to impossible, but would result in a chart many feet or yards in height. Hence, spectral lines are ordinarily arbitrarily shown in one of three ways - namely, as plotted by the particular instrumentation, as triangles of arbitrary base, or as rectangles of arbitrary base. We have chosen to use the third method in the present case, plotting each line as though it has an arbitrary spectral width of 1 nm. The height of the resulting rectangle is such that the area enclosed is proportional to the radiant power available. On some other sources wherein the spectral lines are broad or tend to extend into overlapping bands we use the first method as best representing the data while affording greater ease of reduction of the data relative to that obtained by the standard.

2. Photoelectric Filter Spectroradiometers

The design and use of a photoelectric filter spectroradiometer was discussed in considerable detail in our previous report (2). Since the preparation of that report, however, the use of this instrumentation has been extended not only to include part of the ultraviolet spectral region, but to include also additional types of mechanical operation and electronic output arrangements.

As indicated in an earlier section, in the routine calibration of 1000-watt quartz-iodine lamp standards of spectral irradiance at this Bureau, the use of a photoelectric filter spectroradiometer has been made standard equipment for the spectral region from the visible to 2.5 microns in the infrared (see figure 11). In this particular instrument the filter disk is rotated manually so that alternate readings may be made on the standard and test lamp at each wavelength setting (determined by the particular filter transmission characteristics). The use of the 510 cps chopper and tuned amplifier permits rapid measurement since the time constants of all the electronic and optical components are low. Automatic recording is possible in this set up, but it has been found to slow up and lower the precision of the measurements.

A photoelectric filter spectroradiometer employing 36 narrow-band interference filters was described somewhat in detail in the previous report (2). The design of this instrument permits covering most of the solar spectral region in measurements on solar simulator sources. Recently the development of new and improved ultraviolet narrow-band interference filters 4/ has made practical its use down to about 0.25 micron. Experiments are presently in progress with the use of these filters in conjunction with the two types of photoelectric cells (phototubes and photomultipliers) and with a picoammeter (vs. the 510 cps tuned amplifier) amplifier feeding into an L&N strip chart recorder. It will probably not be necessary to employ the more elaborate (Brower) lock-in amplifier in any of the measurements with the narrow-band interference filters.

To cover the ultraviolet spectral region (300 to 400 nm) a compact instrumentation has been assembled through the use of 9 narrow-band (one/half band width 10 nm) interference filters with pass bands centered at (or near) 310, 320..., and 390 nm (see figure 12 for the spectral transmittance of several of the filters). These are arranged at nine (of twelve) positions on a filter disk, spaced 30° apart so that through the use of a geneva drive (intermittent motion assembly) 5/ mechanism each filter is placed in position for a fixed time interval (say, 10 seconds) after which the next filter in line is similarily placed into position. Three "blanks" permit a 25-second and a 15-second zero each revolution of the filter disk. Thus the recorder chart shows

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4/ Obtainable from the Eppley Laboratory, Inc., Newport, R. I., or from Thin Film Products, Inc., 169 Bridge Street, Cambridge, Mass.

5/ Geneva drive mechanisms of this type are available from Pic Design Corp., 477 Atlantic Avenue, East Rockaway, L. I., New York.

9 horizontal levels representing the irradiances at the 9 spectral intervals isolated by the 9 interference filters. Calibration of the instrument is accomplished simply by placing a standard lamp (in its mounting rack) in position in lieu of the test source. Since the observed responses are much greater through the longer wavelength ranges, these are reduced to approximate those at shorter wavelengths through the use of additional filtering. This is readily accomplished through the use of perforated screens and glass color filters. This procedure is necessitated in order to keep all readings within a reasonable range on the recorder chart. Differences between standard and test source can be handled through changes in the amplifier sensitivity setting.

V. Concluding Remarks

This report supplements earlier ones (1,2) whose review is required to properly assess the results recorded in the present one. Conclusions in regard to the best instrumentation for use in the measurement of the spectral irradiances from solar simulators and solar simulator sources remain much the same - namely, for primary use we recommend the conventional spectroradiometric method in which an integrating sphere is employed and the incident beam of flux is chopped, permitting ac amplification. For supplementary measurements, the photoelectric filter spectroradiometer is recommended for use in this area. In fact, its use may be made the sole instrumentation for checking a solar simulator, or simulator source after its spectral irradiance has once been carefully surveyed by means of the more elaborate prism spectroradiometer.

Table I. Spectral Irradiance of 1000-watt Tungsten-Filament Quartz-Iodine Lamps in Microwatts per (cm^2 - nm) at a Distance of 50 cm When Operated at 8.30 Amperes.

λ,nm	QM-11	QM-12	QM-13	Mean
250	0.0189	0.0220	0.0207	0.0205
260	.0340	.0389	.0367	.0365
270	.0582	.0650	.0619	.0617
280	.0934	.103	.0984	.0983
290	.141	.155	.148	.148
300	.201	.221	.212	.211
320	.382	.416	.402	.400
350	.874	.937	.914	.833
370	1.34	1.43	1.40	1.39
400	2.32	2.46	2.41	2.40
450	4.51	4.76	4.68	4.65
500	7.50	7.76	7.65	7.64
550	10.8	11.2	11.0	11.0
600	14.2	14.7	14.4	14.4
650	17.5	18.1	17.8	17.8
700	20.5	21.0	20.9	20.8
750	22.5	23.1	22.9	22.8
800	23.8	24.4	24.2	24.1
900	24.6	25.2	25.1	25.0
1000	24.0	24.6	24.5	24.4
1100	22.4	23.0	23.0	22.8
1200	20.4	21.0	21.0	20.8
1300	18.4	18.9	18.9	18.7
1400	16.5	16.9	16.9	16.8
1500	14.6	14.9	15.0	14.8
1600	12.9	13.1	13.2	13.1
1700	11.3	11.4	11.5	11.4
1800	9.80	9.90	9.98	9.89
1900	8.49	8.59	8.62	8.57
2000	7.33	7.42	7.45	7.40
2100	6.39	6.50	6.50	6.46
2200	5.69	5.72	5.75	5.72
2300	5.04	5.10	5.14	5.09
2400	4.56	4.60	4.64	4.60
2500	4.18	4.19	4.26	4.21

REFERENCES

1. Ralph Stair, William E. Schneider, William R. Waters and John K. Jackson, Development of Improved Method of Measurement of Spectral Irradiance from Solar Simulators, NBS Report 8539, July 1964.

2. Ralph Stair, William E. Schneider, William R. Waters, John K. Jackson and Roger E. Brown, Some Developments in Improved Methods for the Measurement of the Spectral Irradiances of Solar Simulators, NASA Report No. CR-201, Washington, D. C., April 1965.

3. Ralph Stair, William E. Schneider, William R. Waters and John K. Jackson, Some Factors Affecting the Sensitivity and Spectral Response of Thermoelectric (Radiometric) Detectors, Appl. Opt. 4, 703 (1965).

4. Ralph Stair and William E. Schneider, The NBS Radiometric Standards and Their Use, The Eppley Foundation, in Press.

5. A. J. Drummond and E. Laue, The Extraterrestrial Solar Spectrum and its Simulation in Space Environmental Test Systems, Proceedings of Joint Symposium on Solar Radiation Simulation, Los Angeles, Calif., 18-20 January 1965.

6. V. K. Zworykin and E. G. Ramberg, Photoelectricity and its Application, John Wiley and Sons, New York (1949).

7. R. J. Cashman, New Photo-Conductive Cells, J. Opt. Soc. Am. 36, 356 (1946).

8. A. J. Cussen, Properties of Photoconductive Detectors and Procedures Used to Measure these Properties, Report No. 144, Naval Ordnance Laboratory, Corona, Calif., 1954.

9. R. F. Potter and W. L. Eisenman, Infrared Photodetectors, A Review of Operational Detectors, Appl. Opt. 1, 557 (1962).

10. W. W. Coblentz, Measurements on Standards of Radiation in Absolute Value, Bul. BS 11, 87 (1914) S227.

11. Ralph Stair, Russell G. Johnston and E. W. Halbach, Standard of Spectral Radiance for the Region of 0.25 to 2.6 Microns, J. Res. NBS 64A, 291 (1960).

12. Ralph Stair, William E. Schneider and John K. Jackson, A New Standard of Spectral Irradiance, Appl. Opt. 2, 1151 (1963).

13. Ralph Stair and William E. Schneider, Standards, Sources and Detectors in Radiation Measurements, Symposium on Thermal Radiation of Solids, San Francisco, Calif., March 1964, NASA Report No. Sp-55, page 217, 1965.

14. Robert D. Moore, Lock-In Amplifiers for Signals Buried in Noise, Electronics 35, No. 23, 40 (June 8, 1962).

15. R. D. Moore and O. C. Chaylowsky, Modern Signal Processing Technique for Optimal Signal to Noise Ratios , Technical Bulletin 109, Princeton Applied Research Corp., Princeton, N. J., 1963.

16. Brower Laboratories, Inc., Model 129 Thermocouple Amplifier, Operating Instructions, Brower Laboratories, Inc., Westboro, Mass., 1965.

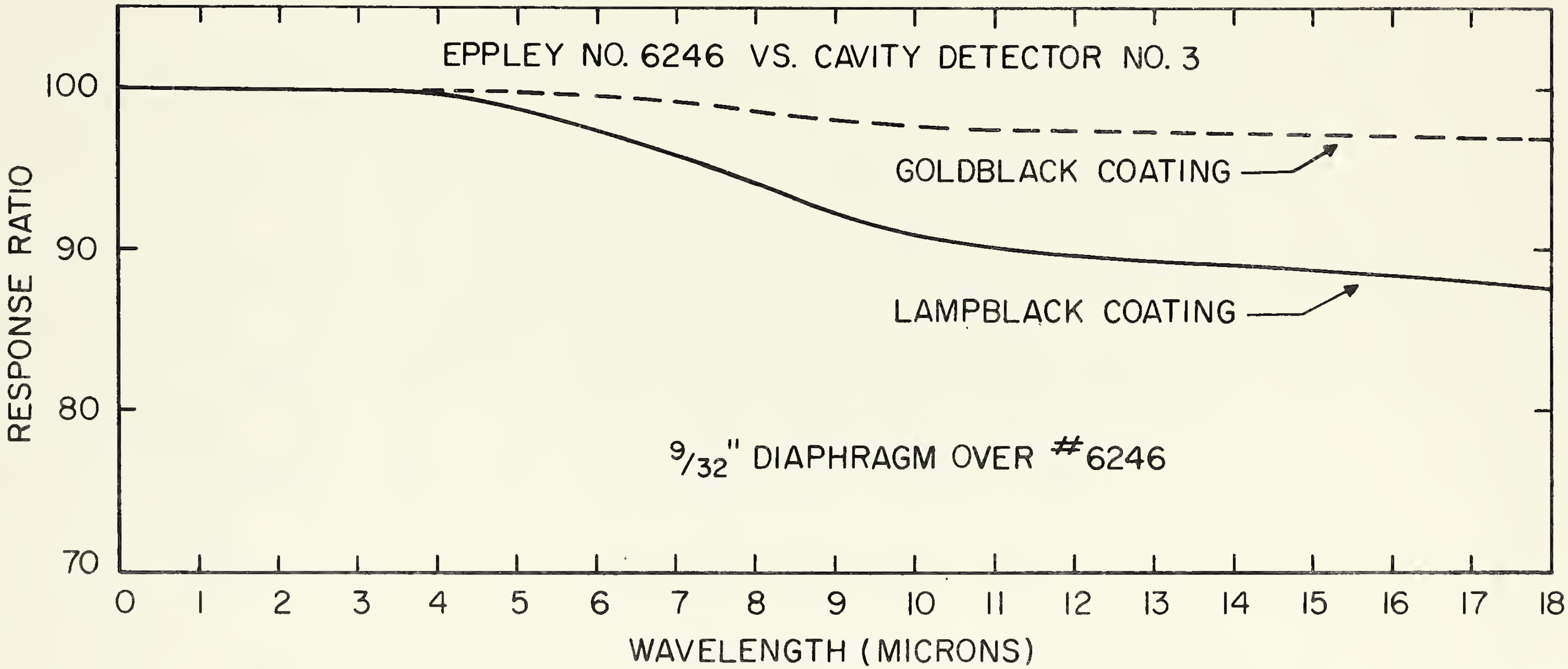

Fig. 1. Spectral Sensitivity of an Eppley Thermopile coated with gold black, and with lamp black versus NBS cavity detector No. 3.

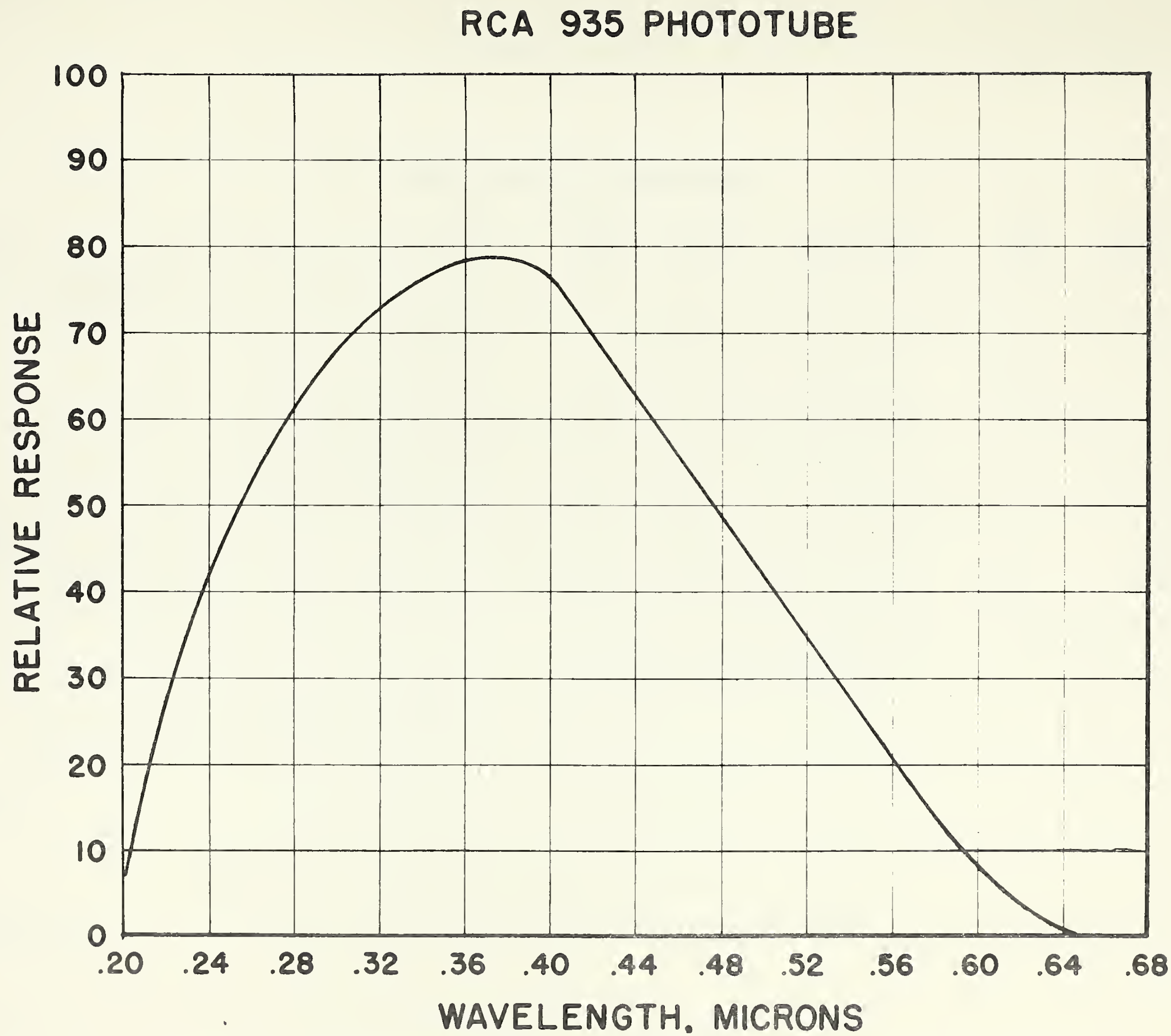

Fig. 2. Relative spectral response for equal energy of an RCA type 935 phototube (NBS data on tube No. 935-1).

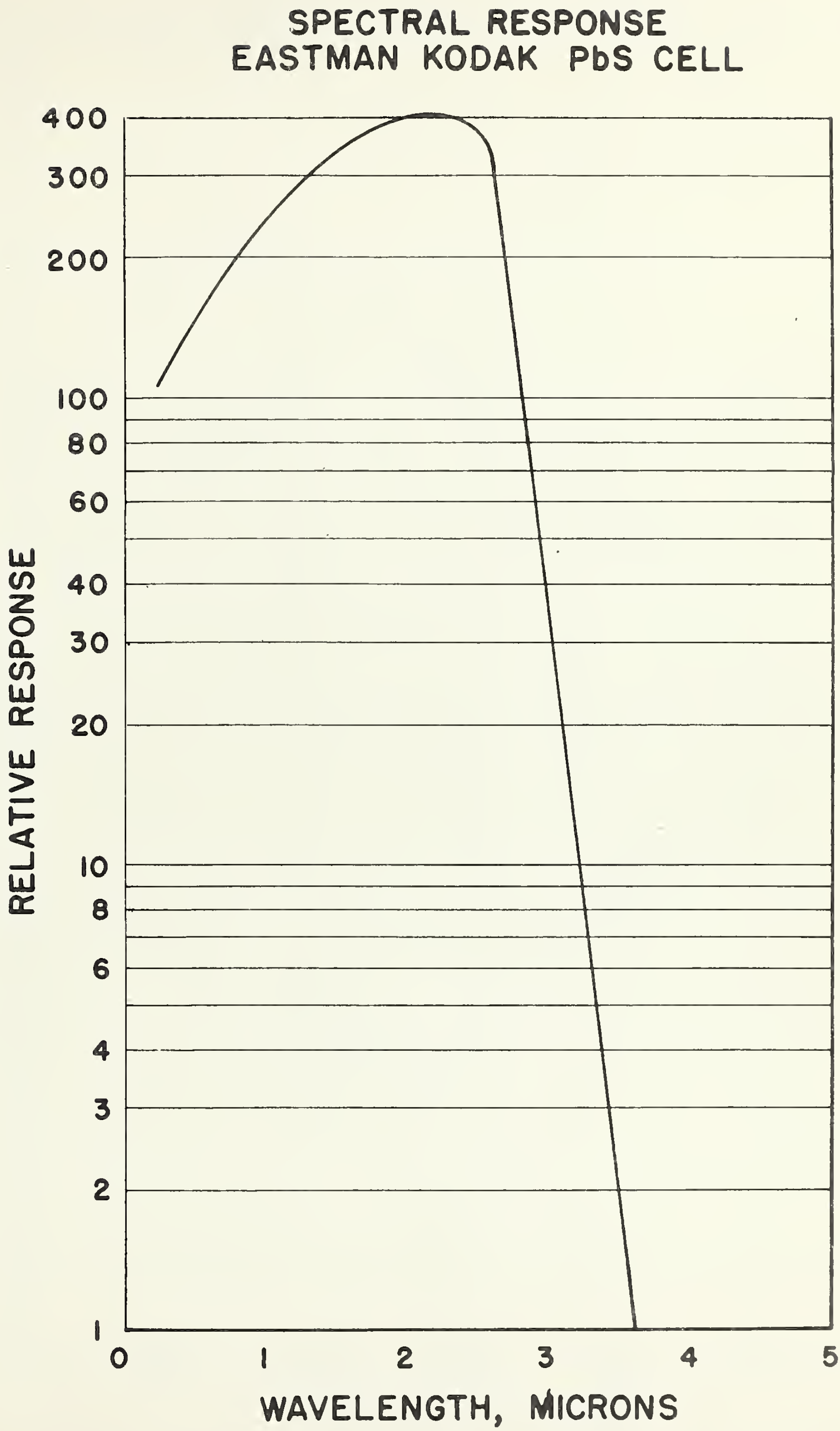

Fig. 3. Relative spectral response of an Eastman Kodak PbS cell (Manufacturers data).

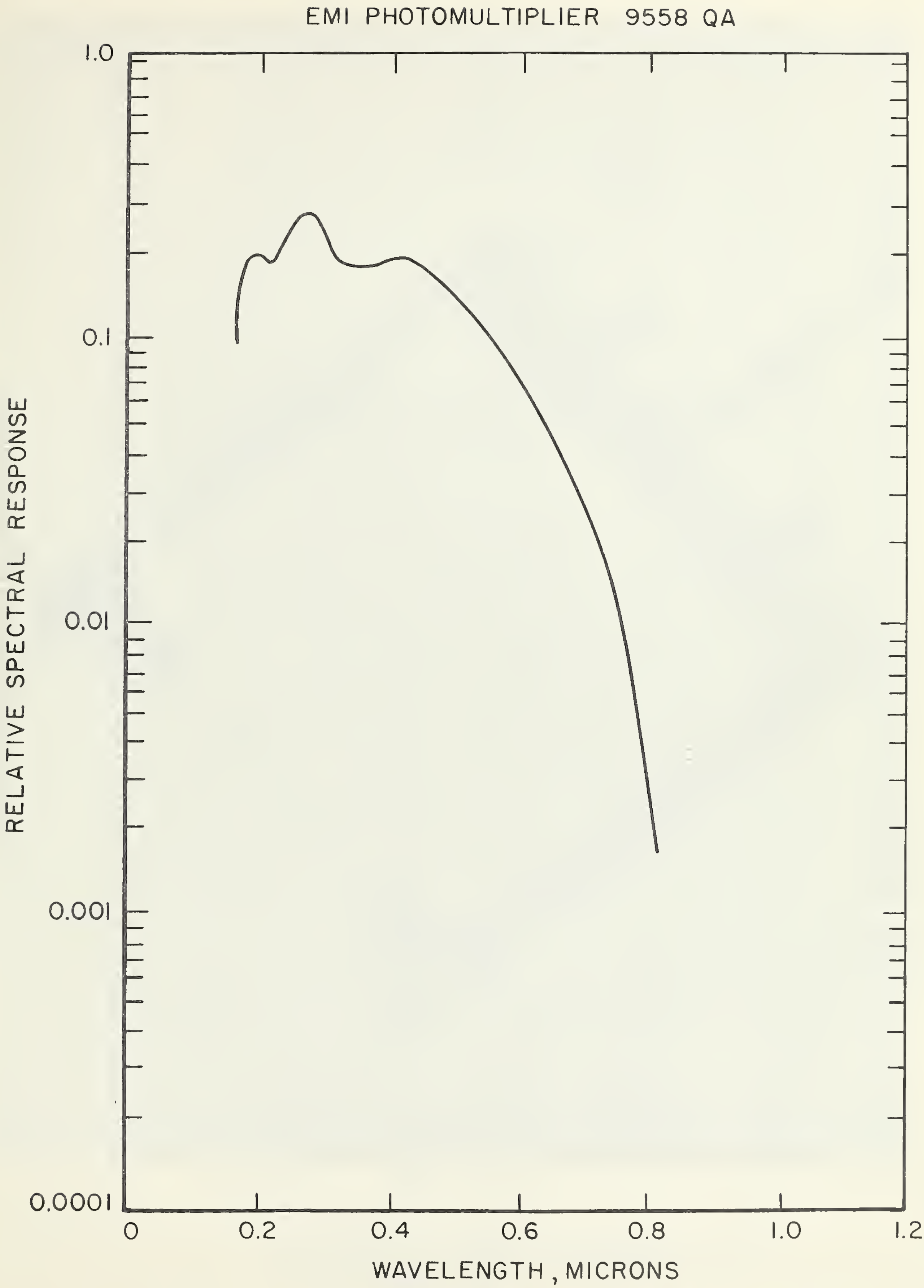

Fig. 4. Relative spectral response of an EMI type 9558B photomultiplier (Manufacturers data).

Fig. 5. The 1000-watt quartz-iodine lamp standard of spectral irradiance mounted in special holder ready for use.

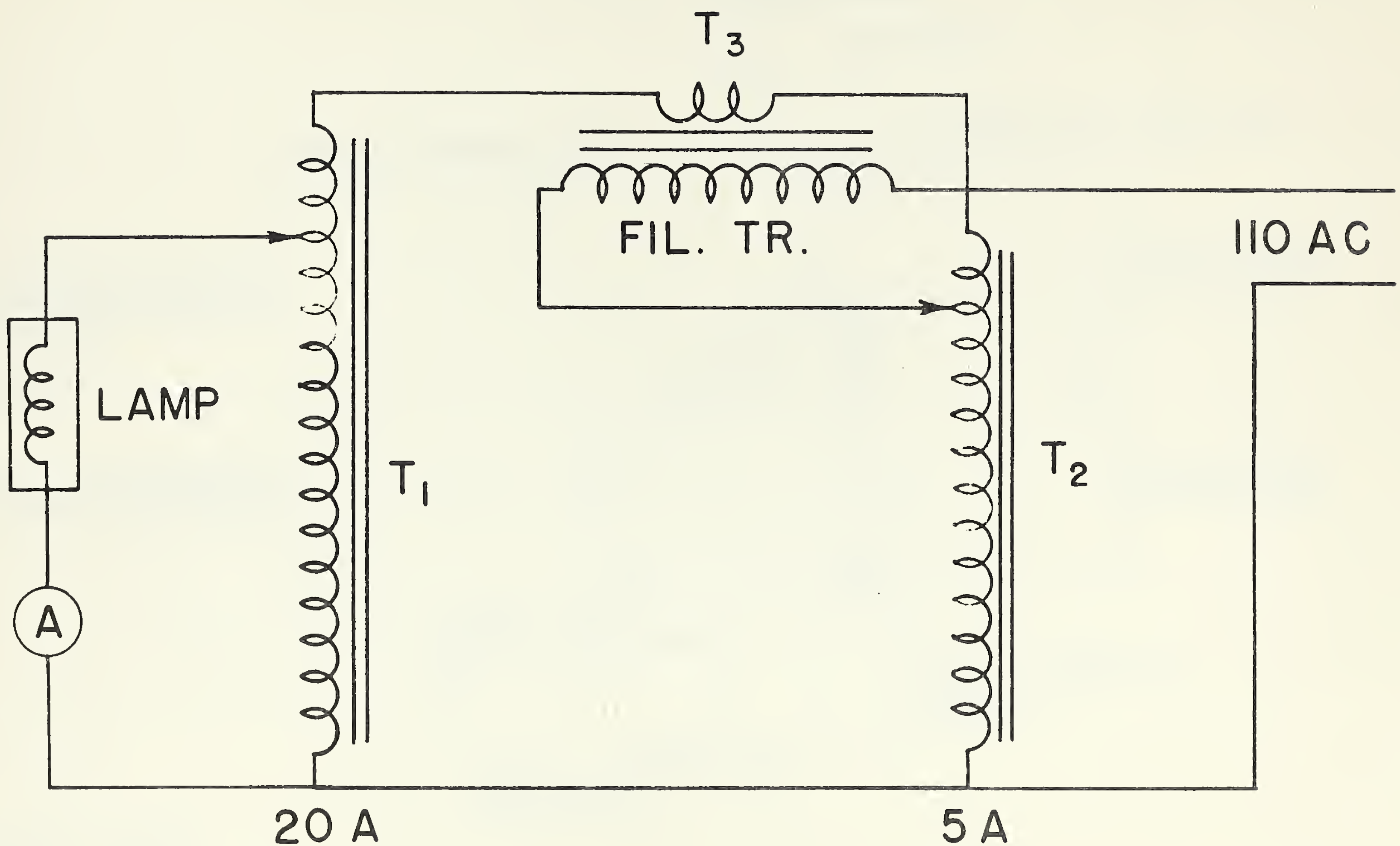

Fig. 6. Electrical ac circuit for standard lamp operation to provide smooth current control.

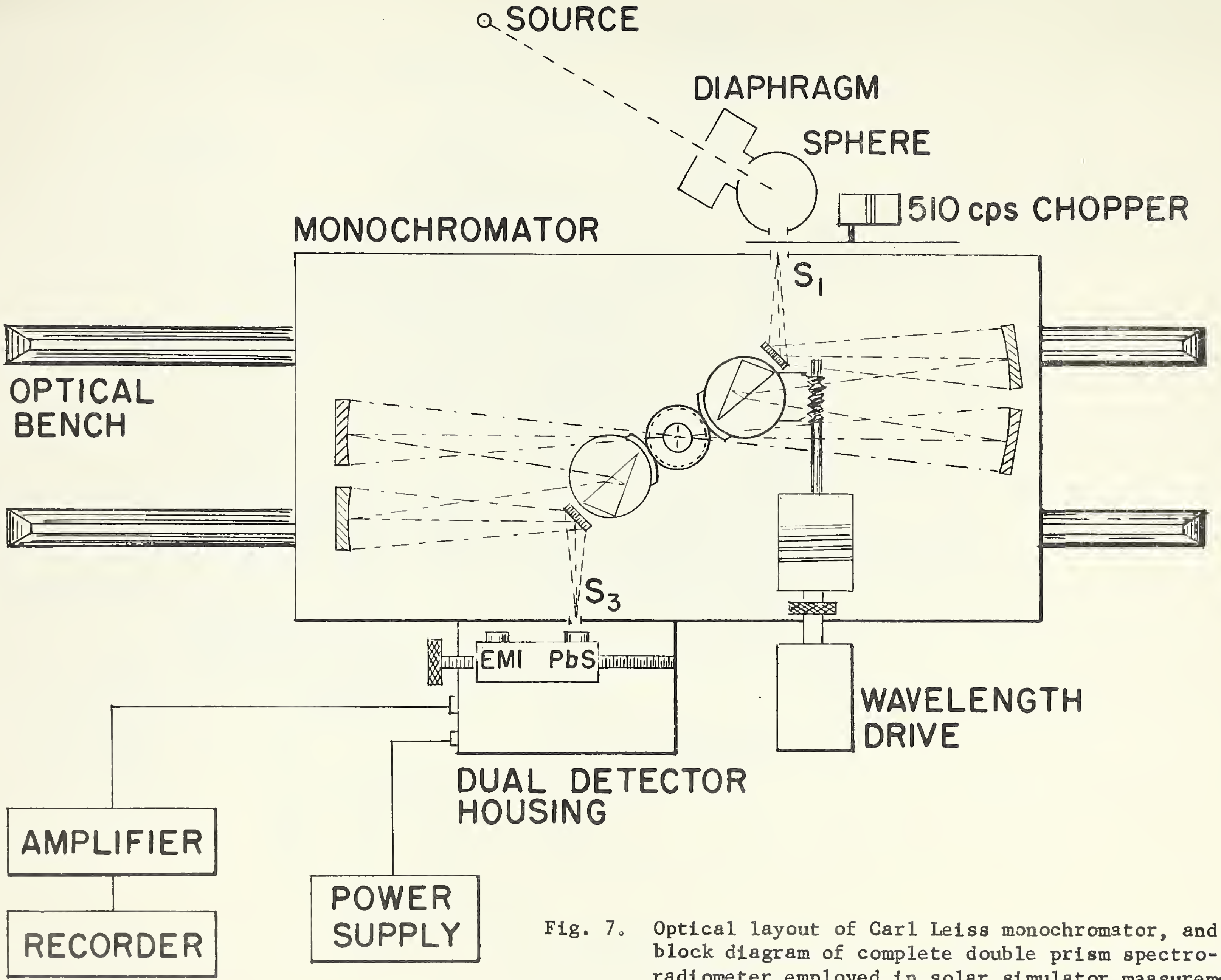

Fig. 7. Optical layout of Carl Leiss monochromator, and block diagram of complete double prism spectroradiometer employed in solar simulator measurements.

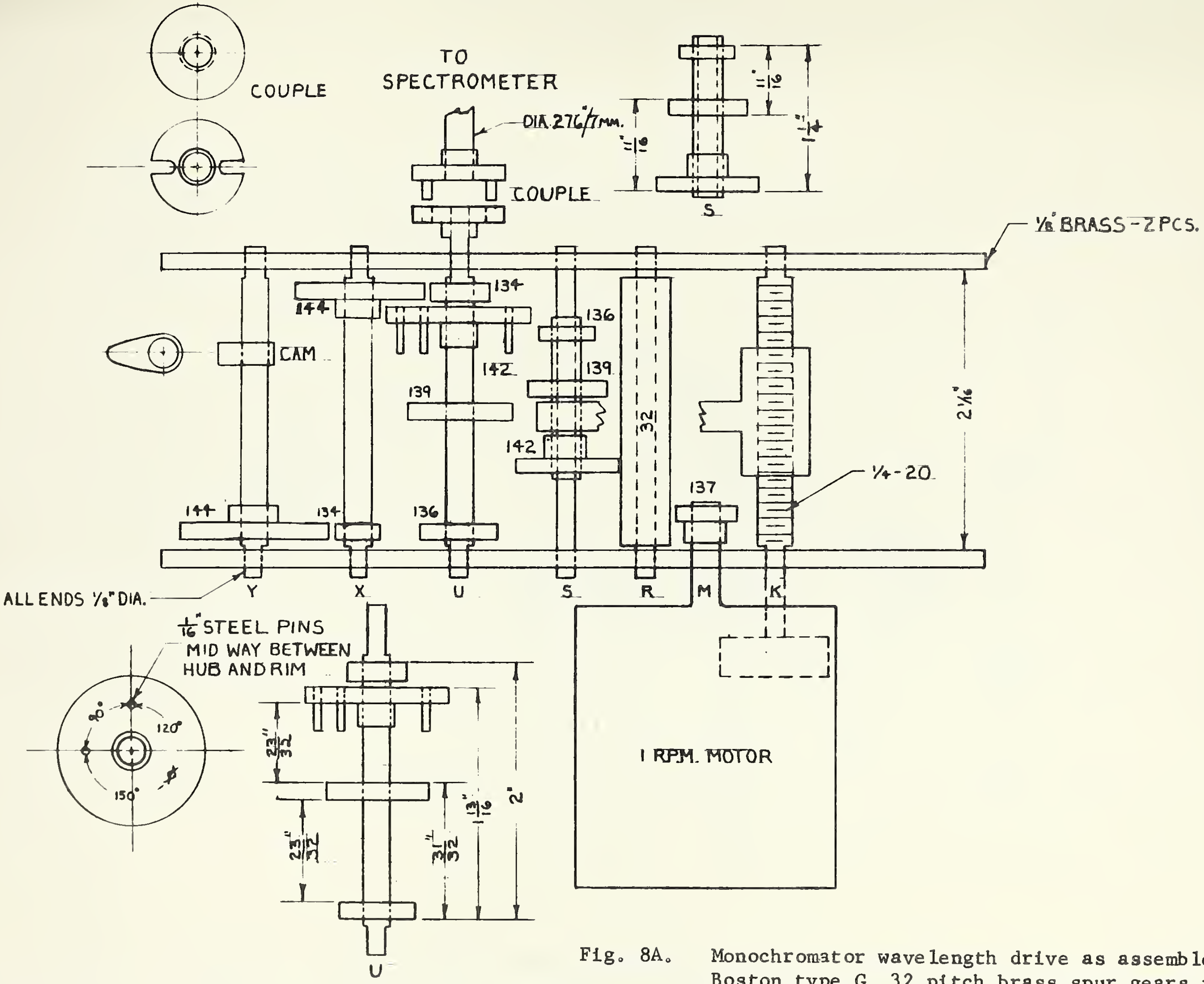

Fig. 8A. Monochromator wavelength drive as assembled with Boston type G, 32 pitch brass spur gears for three speeds forward and reverse. Gears spread out to show general arrangement.

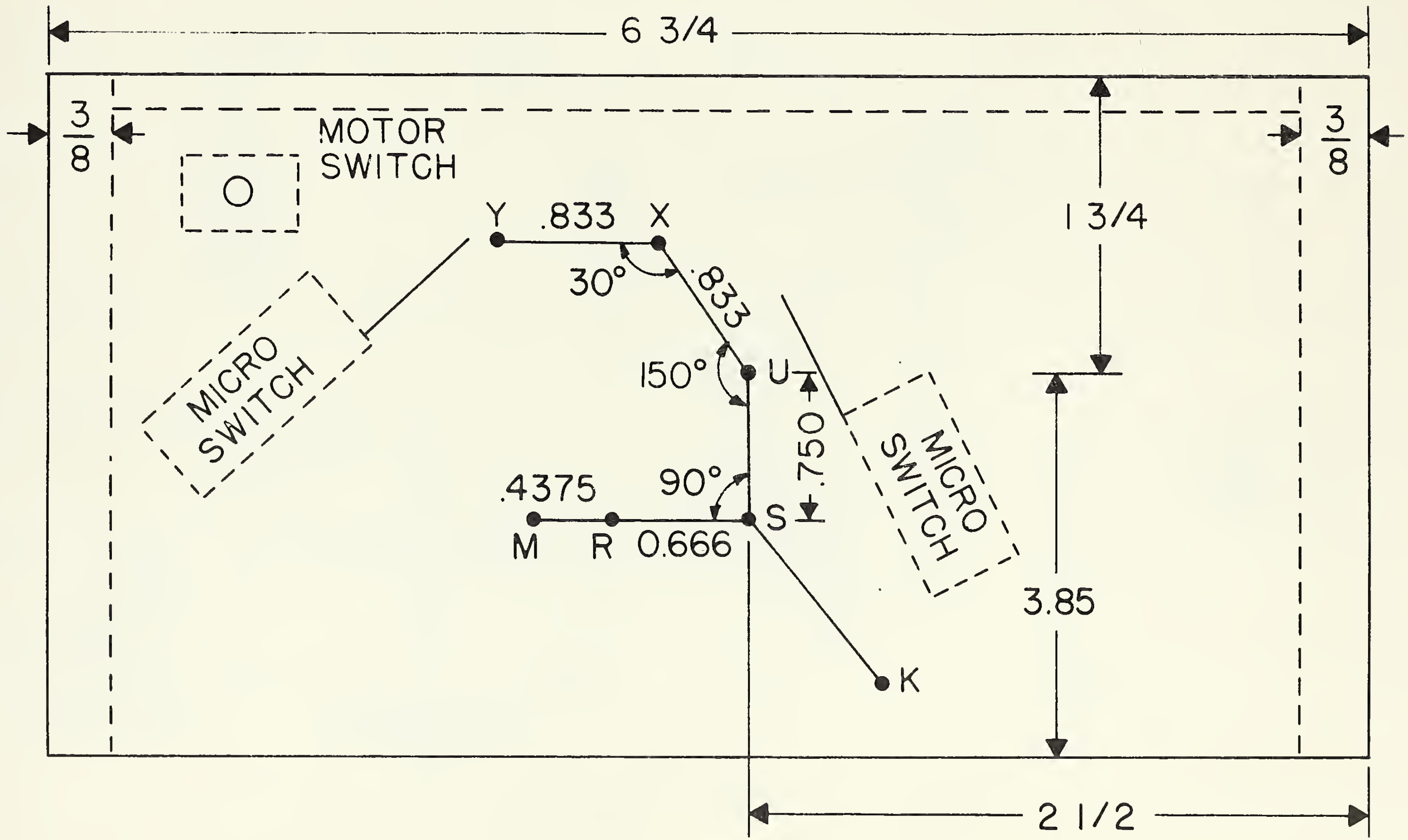

Fig. 8B. Specific shaft locations of monochromator wavelength gear drive assembly.

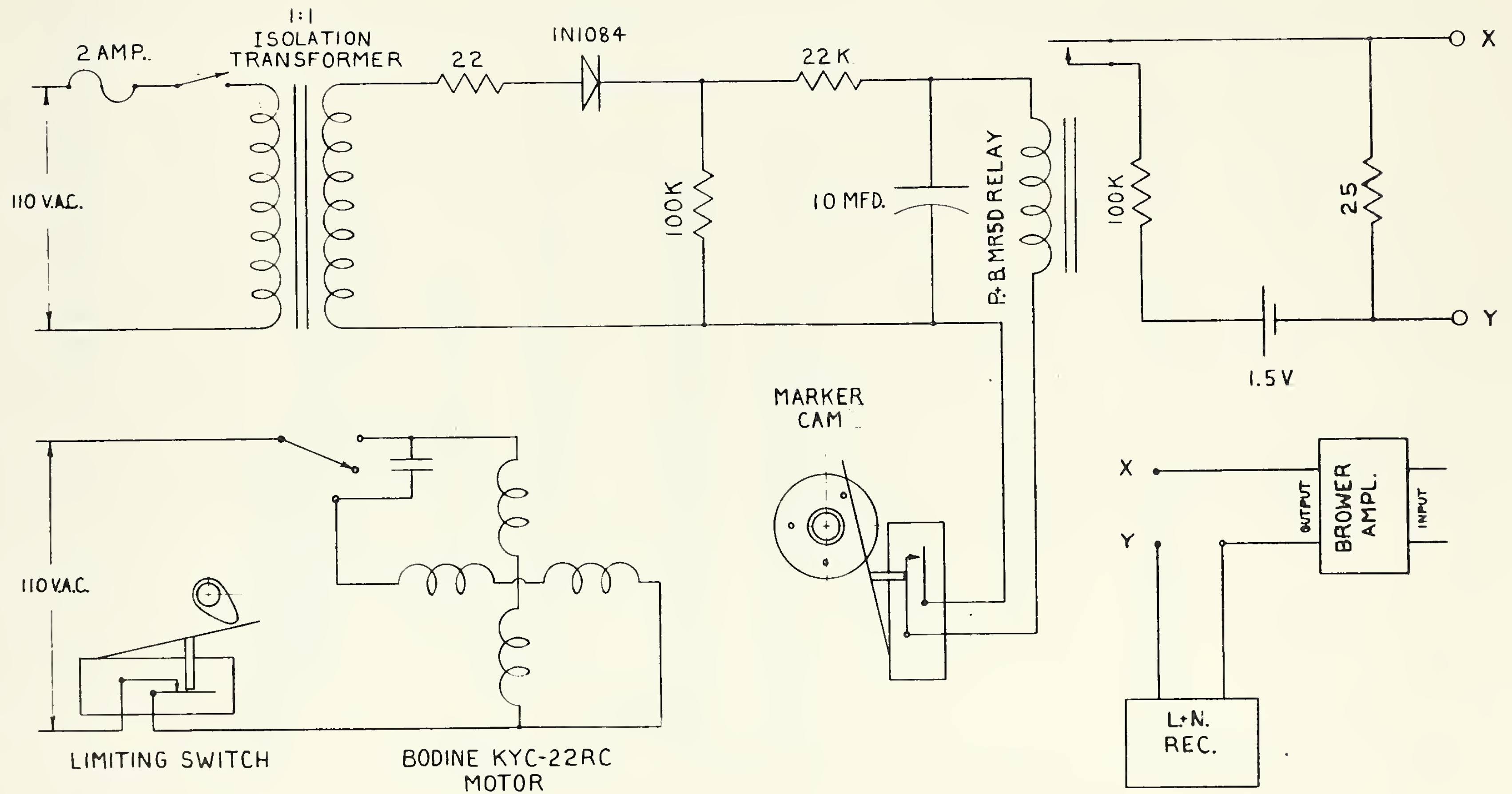

Fig. 9. Electrical circuit of wavelength indexing mechanism.

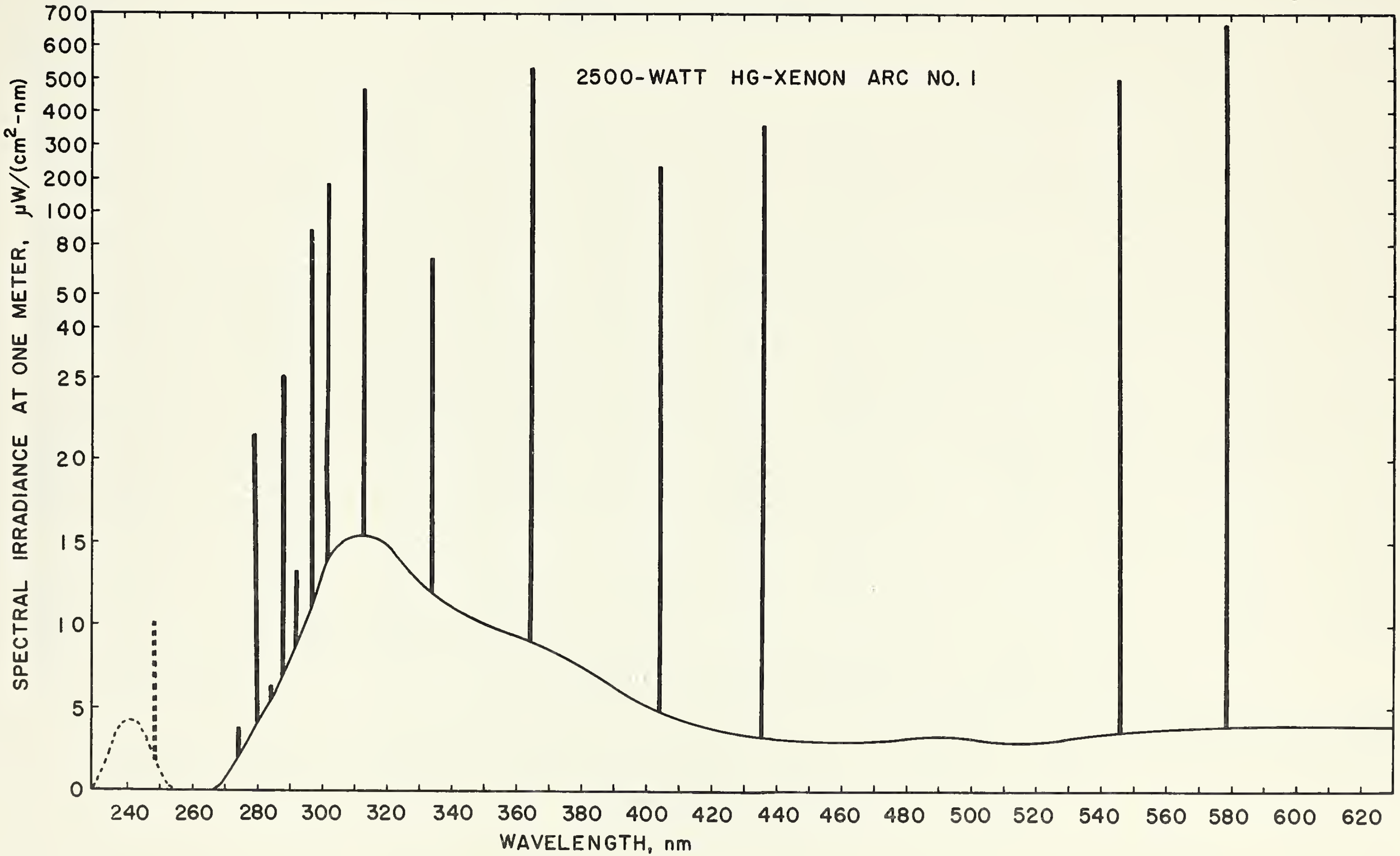

Fig. 10A. Spectral irradiance from a 2500-watt Hg-Xenon arc lamp at a distance of 1 meter in micro watts per $(cm^2\text{-nm})$. Spectral range from 250 to 620 nm. Values below 250 nm approximate. Note: Scale is non-linear.

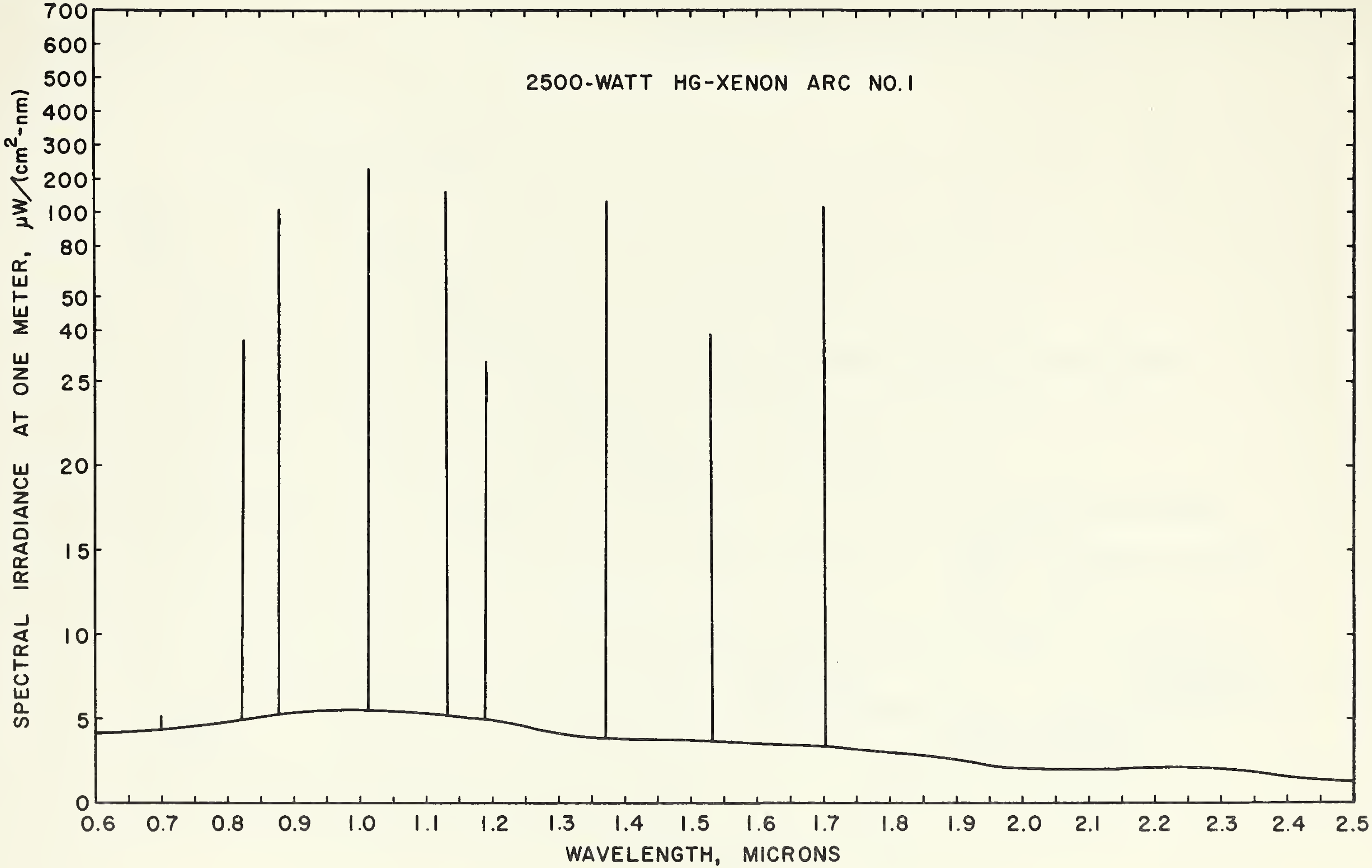

Fig. 10B. Same as Fig. 10A. Spectral range from 0.6 to 2.5 microns.

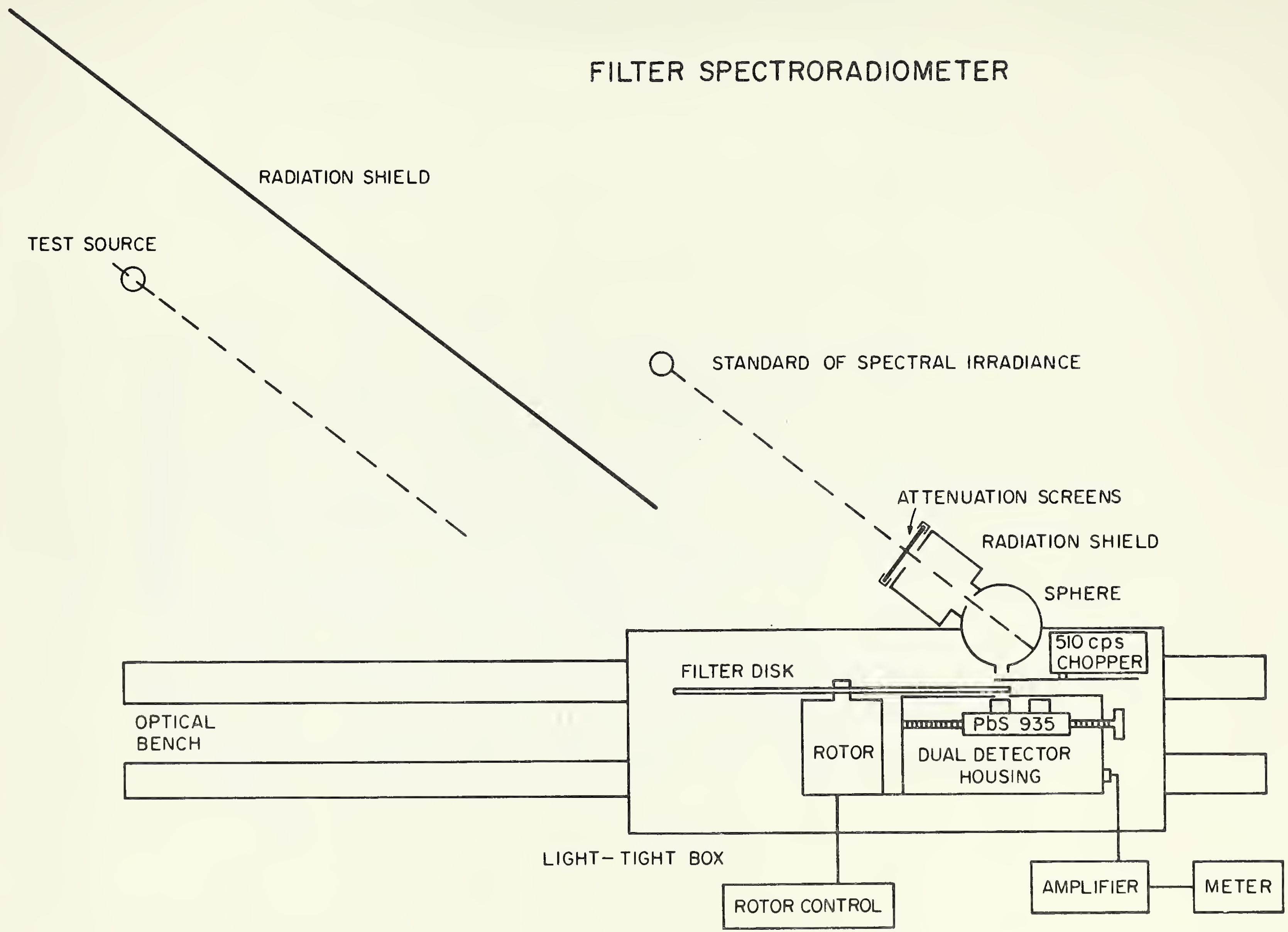

Fig. 11. Block design of photoelectric filter spectroradiometer with 510 cps chopper and antenna motor-rotor.

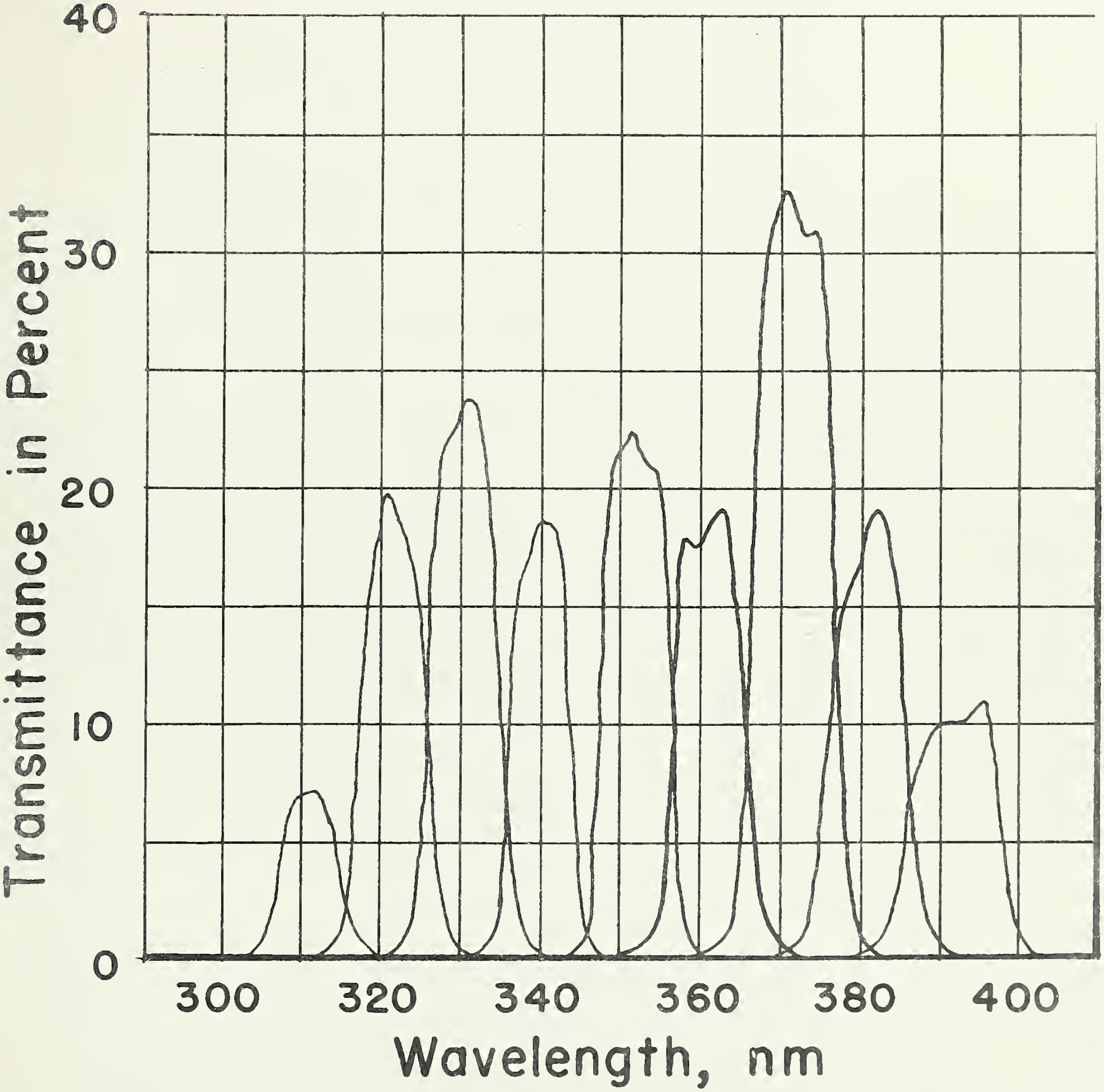

Fig. 12. Transmission curves for several of the special narrow-band-pass interference filters employed in one of the photoelectric filter spectroradiometers.

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